GEOLOGY OF ALTERNATE ENERGY RESOURCES

HOUSTON GEOLOGICAL SOCIETY

MICHAEL D. CAMPBELL

PREFACE

The Houston Geological Society, in its desire to assist in the orderly development of energy and energy-related resources, is most pleased to publish the text: *Geology of Alternate Energy Resources in the South-Central United States*. Because of our declining domestic oil and gas resources and the increasing need to import both oil and gas resources from insecure foreign sources to meet our increasing demand for energy, this publication, in response to our Nation's urgent need to develop regional alternate energy sources, is most timely.

The text evolved from a session on alternate energy resources of the Geological Society of America, South-Central Regional Meeting held in February, 1976 at Rice University, Houston, Texas. Mr. Michael D. Campbell, of the Department of Geology, Rice University served as Convener of the session "Alternate Energy Resources." The session was co-sponsored by the Houston Geological Society. The co-chairmen for the session were Dr. Ted H. Foss and Dr. John S. Dudar. Based on the outstanding interest indicated by those in attendance at the session, Dr. Anthony Reso, President (1975-76) of the Houston Geological Society, suggested the possibility of HGS publishing the five papers given during the session. In due course, Mr. Campbell proposed to the HGS Executive Board an expanded plan for publication of a comprehensive review of the geology of the three alternate energy resources of the South-Central United States (uranium, lignite and geopressured geothermal energy). The plan was adopted by the Executive Board and this text is the result. Mr. Campbell was designated Editor, and he in turn appointed Ms. Patricia W. Dickerson of Gulf Oil Research and Development Corporation as Assistant Editor.

The need for development of alternate energy resources has become painfully apparent to the general public during this extremely cold winter of 1976-1977. The energy industry has known and predicted for years that the development and utilization of such resources will be mandatory. This text documents the extent of industrial, governmental and academic effort over the past few years and presents the potential and technical status of the development of alternate energy resources with environmental consciousness in the South-Central United States.

The text is intended for managerial and technical personnel who are either presently involved in or are anticipating an entry into alternate energy exploration and development. It will also be valuable as a reference source and as a text in teaching the subject material at the college-university level. The Houston Geological Society trusts that the text will be useful to industry, government and the academic community.

The Houston Geological Society acknowledges Mr. Campbell's outstanding efforts in the development of the text's concept and in the overall preparation and editing of the text. The HGS also acknowledges Ms. Dickerson's editorial and production guidance. In addition, Ms. Mary Wiley Hodge, as Production Editor, accomplished the difficult task of editing the manuscripts during production. Ms. Francis Lauve graciously assisted Ms. Hodge and devoted considerable time to page proofing. The Society is also most appreciative of the efforts of the contributors of each chapter of the text for their outstanding and timely presentations.

March, 1977
Houston, Texas

Hal H. Bybee
President (1976-77)
Houston Geological Society

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INTRODUCTION

Oil and gas reserves are declining nationwide at an alarming rate. Alternate energy resources such as uranium, coal (including lignite), and geothermal energy must play dominant roles in the American economy in the near future. Fortunately, alternate energy resources are regionally abundant in the United States and if developed with appropriate consideration to the environment, they will serve to bridge the gap between our present petroleum-based energy systems and future solar or fusion-based energy systems (Newell, 1976). It is clear that a diversified multiple-energy base must be developed to serve our regional energy needs well into the twenty-first century (Campbell, 1976).

The south-central states were once endowed with abundant oil and natural gas resources. But, as domestic supplies begin to dwindle and as the economic incentive for producers to develop oil and natural gas deteriorates, energy consumers must now begin to seriously consider substitute sources of energy to satisfy the region's future energy requirements. However, any major industrial change-over to other energy sources will require years of planning, evaluation, research, exploration and development before they can adequately meet our energy and raw materials requirements; hence there can be no further delay.

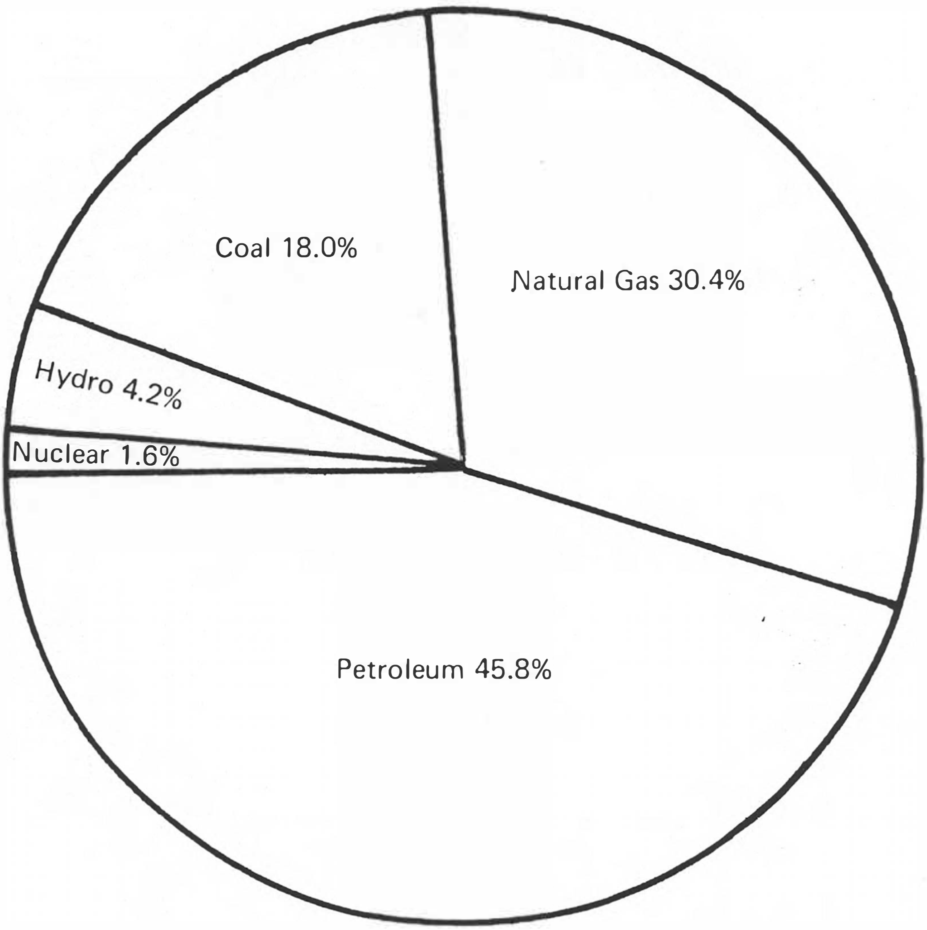
The South-Central United States is well endowed with alternate energy resources in the form of uranium, coal (lignite), and geopressured geothermal energy. This volume presents a review of what may become the region's major sources of energy in the foreseeable future, and is intended to be a state-of-the-art analysis of the total spectrum of regional energy resource assessment. Although regional in scope, the techniques of assessment and the developmental approaches explored in this text have significant application to other regions of the United States as well as to other nations.

Each of the three alternate energy resources (uranium, coal (lignite) and geopressured geothermal energy), will be examined in terms of the four factors involved in resource assessment: 1) New (Frontier) areas of exploration, 2) Known (Trend) areas of exploration and development, 3) Resource development or utilization, and 4) Environmental considerations affecting the development of the resource. A Selected Bibliography is included to augment the technical coverage of each of the three resources examined. As an introduction to the chapters that follow, a brief summary of the present domestic energy picture is presented to emphasize the manifest need for alternate energy resources and the role that the South-Central United States can play in meeting that need.

As of 1974, the United States consumed approximately 73 quadrillion (10^{15}) Btu, of which petroleum supplied 45.8%; natural gas 30.4%; coal (including lignite) 18.0%; hydropower and geothermal energy 4.2%; and nuclear power 1.6% (Figure 1). Energy consumption is growing domestically at an average rate of approximately 5.0% per year, but the growth rate is expected to decline slowly to approximately 3.0% per year in the next few decades. The Federal Energy Administration (FEA) conservatively estimates that the nation's total energy needs 16 years

ENERGY CONSUMED IN THE UNITED STATES BY SOURCE IN 1974

(Consumption 73.1 quadrillion Btu)



U.S. Department of Interior News Release, April 3, 1975

FIGURE 1.

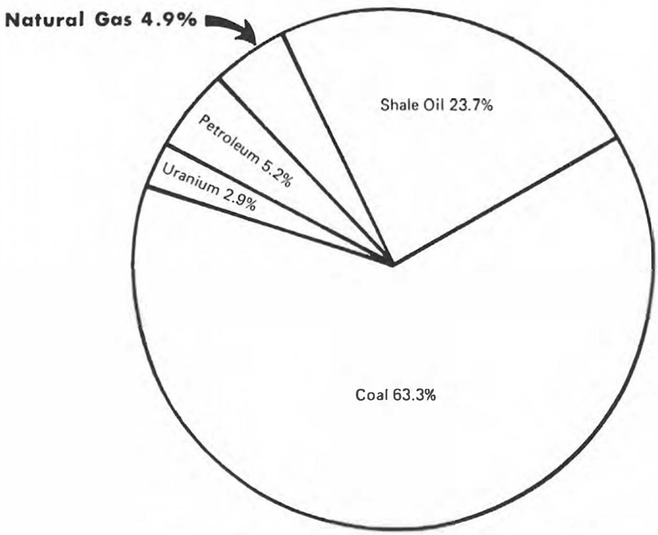
hence (1990) will increase to 112 quadrillion Btu, or about 53% more than the Btu consumed in 1974 (U.S. Dept. Interior, 1975). Presumably, this estimate assumes no change in standards of living or present levels of energy waste.

Federal estimates, in an attempt to place these requirements in perspective, have suggested that the total energy *available* from domestic fossil and nuclear fuels is approximately 55.6 quintillion (10^{18}) Btu (Figure 2). These estimates, however, although based on the most reliable data available at the time, included only a conservative view of available energy from conventional sources. As will be indicated in this text, the potential for additional energy resources (in the South-Central United States, at least) is excellent.

The Federal estimates show that domestic reserves of coal (not including the full potential of available lignite) contribute more than 60% of the potentially available energy. If used solely for energy production, coal alone could supply energy for more than 300 years at the 1990 Btu consumption rate. Ranking second in Federal estimates of potential is oil shale and sands, although no significant production has yet been achieved because of technical problems (Pforzheimer, 1976). Such resources have an uncertain role in the overall energy picture, although the Federal government has supported a reasonable research and development effort over the past five years.

Sources Of Energy For Future Needs In The United States

Total available energy is estimated at 55.6 x 10^{18} Btu



Federal Power Commission "National Gas Survey," 1974

FIGURE 2.

Placed in the above framework, the estimates show that petroleum and natural gas account for only 10% of the total potential energy available from fossil fuel, although together they currently supply more than 75% of the total energy consumed (compare Figures 1 and 2). It should be clear then that we are presently overutilizing our most limited resources (oil and gas) and underutilizing our most abundant immediate resources, uranium, coal (lignite) and geothermal energy.

The overemphasis on oil and gas as the most important forms of energy evolved from the economically sound choice of those resources that were most easily converted to Btu. However, disproportionate utilization of resources has not only caused overdevelopment of our own and foreign prime energy resources (oil and gas), it has also made us increasingly dependent on foreign oil-producing countries for a substantial part of our energy needs. Any change in industrial and societal habits is difficult, especially in terms of our use of energy, and we are presently beginning to experience the normal effects of an open, capitalistic economic system. What we pay for energy depends on supply and demand. If the supply of a particular energy source is short, not only will the price be relatively high but there will also be no assurance that it will continue to be supplied, especially if we resist, via the media and our representatives in Washington, paying the price of either domestically or foreign-produced energy. If there is no alternative, there is also no choice.

Superimposed on this assumed natural system of supply and demand economics is the significant political influence which has strongly affected the development and over-exploitation of our prime energy source and has prevented the development of alternate energy sources. Although Washington "politics" have been responsible for creating many of the obstacles and restraints to the natural development of an open supply-and-demand system (Winger & Nielsen, 1976), the energy industry has, in the course of pursuing the free enterprise system, naturally attempted to maximize profit potential by developing the most economic source of energy. If a demand is present, industry will endeavor to meet that demand at a price that the energy consumer will pay; however, because of past governmental restraints on prices, energy consumers are presently faced with prices they are unwilling to but must pay because they have no present alternative in their consumption patterns. The development of alternate energy sources has not been considered a viable economic venture until recently. As energy prices escalate, new sources of energy naturally become economically viable. A source once economically unattractive to develop may become feasible, if an economic advantage is defined. The early signs of industrial diversification of interest in a multiple-energy base have been apparent for the past few years (see Figure 3). This is a natural development, although since we have failed to diversify earlier, the interim period of industrial and societal adjustment will be plagued with short supplies of conventional energy and relatively high prices, which will continue to rise.

The role of government in this period of diversification should be two-fold. First, in an attempt to assist the industrial sector, the government should foster cooperative research and development of all potential alternate energy sources. At present industry does not have the economic incentive to evaluate or develop a particular potential energy source because of unclear governmental requirements. Secondly, government, in representing the consumer, should also protect society against industrial abuses of the environment and bring into balance

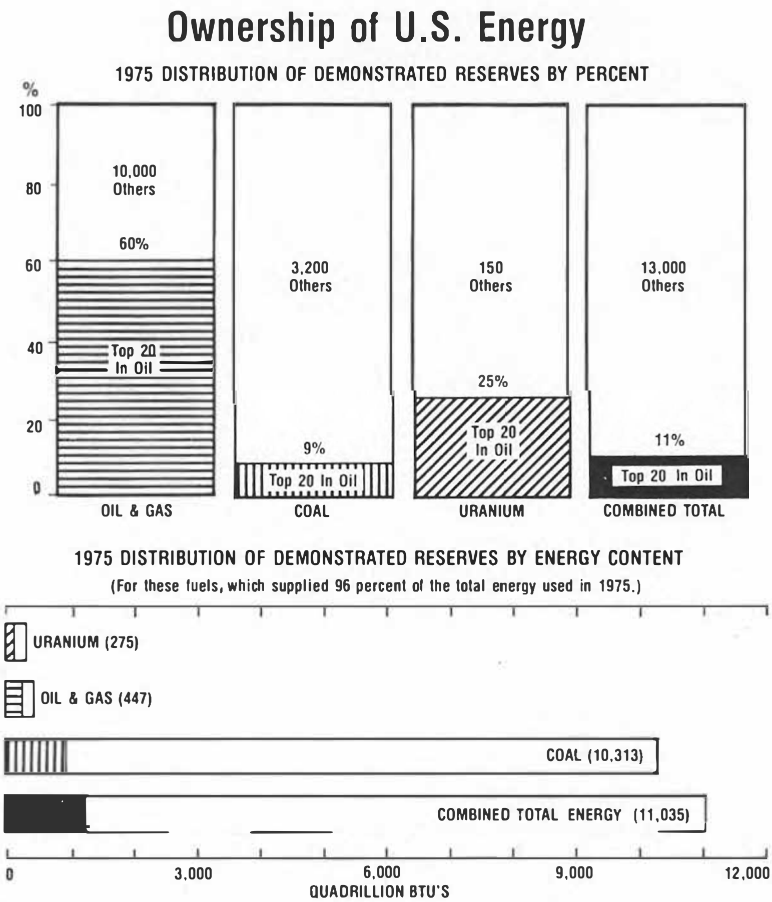


FIGURE 3. Distribution of ownership of energy reserves by percent and by energy content showing role of the top twenty petroleum companies as of 1975 in the energy field, including oil and gas, coal and uranium. (After U. S. Dept. Interior, *Energy Perspectives 2*, 1976; U. S. Bureau Mines; Keystone Coal Industry Manual, U. S. Coal Production by Company, 1975; Society of Petroleum Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers.)

environmental costs and benefits. In addition, society should be protected against possible violations of antitrust laws that undermine the natural, free enterprise system of supply and demand. Rapid industrial development has provided jobs and opportunities to produce the greatest economic growth and highest living standard in history, but this accomplishment has had its price, a price consumers have not been willing to pay; consequently, degradation of our environment and natural resources has occurred.

As has been witnessed, however, abuses of government via unreasonable environmental and pricing regulations have created an adversary relationship between government and industry in many areas. The perspective of the "happy medium" has been lost over the past few years. Government, in attempting to represent the people and the so-called objective overview, has not only grown in power, purportedly to match the powerful efforts of big industry and to protect us from ourselves, but has by doing so also dampened industrial enthusiasm to venture into new areas of energy development with innovative ideas and financial support.

Although the problems of energy development are complex, in the final analysis, industry's prime objectives are: 1) to make a profit and 2) to serve the people by anticipating their future needs. Without the collective support of the public, however, the energy industry, as we know it today, will not survive the difficult years of diversification and readjustment ahead. The arrival of plentiful, inexpensive energy from fusion or other sources may be at least 25 years in the future. The "tug and pull" of industrial development with environmental consciousness is a natural phenomenon and to be expected in a complex, open society. Although not readily apparent to some, history will surely show that progress is under way and a regionally-diversified, multiple-energy base of nuclear power, coal, and geothermal energy will be developed, and within a socially-cognizant free-enterprise system.

Nuclear Energy Potential. Nuclear power will play an increasingly significant role in nationwide electrical generation. The apparent lack of available domestic uranium resources is one of the major problems that is presently confronting the nuclear-power generating industry. If the other technical and environmental problems regarding nuclear-reactor safety (Doctor and others, 1976) and plutonium-handling (Feivesion and others, 1976, and Anonymous, 1976) are satisfactorily resolved for nuclear development (Anonymous, 1976), the present cycle of construction of light-water reactors will require substantial uranium reserves until the breeder reactor becomes operational, probably in the late 1990's (Energy Resources Council, 1976). If and when the breeder reactors become operational, they will utilize the partially consumed uranium from the light-water reactor fuel cycle to produce an additional 70 quintillion (10^{18}) Btu, or 14 quintillion Btu more that the 1974 estimates of the total *available* domestic energy and more than twice the Btu available from the present estimates of coal resources (see Figure 2).

The present need, however, is to stock the light-water reactors that are either presently in operation, under construction, or planned for the near future (see Figure 4). As mentioned earlier, the nuclear development program has proceeded cautiously over the past few years since potential environmental and technical safeguards associated with reactor safety and plutonium-handling have slowed construction in an attempt to resolve the pending questions. Voter referendums, however, on the public question of nuclear development were approved by a 2-1 margin in six states (Anonymous, 1976b). The public, therefore, has indicated that energy alternatives are necessary.

As of the present time, nuclear power has assumed approximately 9.8% of all domestic electrical production, well above previous expectations. In 1974, for example, approximately 6.0% of all electrical generation was produced by light-water nuclear power plants. Until recently, the exploration and producing companies have not had sufficient economic incentive to respond to staggering projected demands, and even now the uranium exploration and

	Thousands of Megawatts	Number of Plants
Under ERDA Enrichment Contract		
Licensed to operate	43	61
Construction permit granted	77	72
Under construction permit review	67	60
Ordered	14	12
Announced	7	6
	208	211
Not Under ERDA Enrichment Contract		
Construction permit granted	1	1
Under construction permit review	6	5
Ordered	7	6
Announced	18	15
	32	27

FIGURE 4. Status of U.S. nuclear power plants as of August 31, 1976 (Parks and Thomas - 1976).

producing companies are hesitant to gear-up too rapidly because they are aware that uranium is a "political" mineral and overexpansion could be a dangerous financial risk (Anonymous, 1976). The rapidly expanding uranium market (Boyden, 1975) has helped to cause serious financial problems for one overly aggressive producer (Anonymous, 1975); other producers have become wary of increasing mining costs and of foreign uranium producers (Anonymous, 1976d; Macgregor and Vickers, 1974). The need for new uranium resources is certain and the South-Central United States may provide a significant percent of the needed uranium reserves, both from new uranium ore bodies and from mining by-products of phosphate (Ross, 1975; Anonymous, 1977).

In Part I of this text, the geological and other technical factors in uranium exploration are examined from the regional (frontier) and the local (trend) viewpoint in Chapters 1 and 2, respectively. Uranium development is explored in Chapter 3 in terms of *in situ* or subsurface solution mining, a method of growing popularity with industry and environmental regulatory agencies. Chapter 4 discusses the position of the U. S. Environmental Protection Agency with regard to the environmental impacts of uranium mining. Chapter 5 is the "Selected Uranium Bibliography." It should be noted that the selected publications appearing in Chapter 5 (and Chapters 10 and 15) do not appear in the previous chapters. The topical bibliography covers recent and background topics on uranium of possible peripheral interest.

Coal (Lignite) Energy Potential. Coal has obviously long been a conventional source of energy. Its widespread use, however, was eclipsed by oil and gas three decades ago when oil and gas became the dominant forms of energy for domestic consumption. Coal production declined, but with the early shock of short domestic supplies of oil and natural gas, coal production again began to climb. Although vast amounts of coal are presently used for steam production, a significant amount is also necessary for use in industrial processes other than energy production. Metallurgical coal is used in steel manufacturing and other industries where high-carbon materials are required.

In the past few years, coal, especially lignite, has been considered for use in the production of synthetic fuels, such as low-Btu gas, pipeline-quality gas, refinery feedstock and solvent-refined products that could be economically attractive substitutes for the decreasing supplies of oil and natural gas (Anonymous, 1976e; Hendrickson, 1975). The extent of resources of the relatively low-Btu lignite in the South-Central United States was not realized until recently, although large reserves of the resource have been known in the North-Central United States for over 40 years and have been included in Federal estimates of total available energy. South-Central resources may be capable of adding 20 quadrillion (10^{15}) Btu to the total available domestic energy reserves.

Substantial resources exist and may serve two additional functions by substituting for conventional sources of energy and by providing by-products (as energy sources for large- or small-scale power generation and as feedstocks for the chemical industry's use in the manufacture of plastic and asphaltic products). The economic viability of lignite utilization is still under study by industry but development seems to be imminent to meet either the needs of a new synthetic fuel industry, the needs of minemouth power-plant complexes (if found to be economic and environmentally cognizant) or the needs of the chemical industry.

In Part II of this text, Chapter 6 discusses the geological and other technical factors involved in regional lignite exploration and project development. Chapter 7 examines some of the local geological characteristics of lignite. Lignite utilization is discussed in Chapter 8 in terms of *in-situ* or subsurface gasification of lignite. Chapter 9 is a summary of the environmental aspects of lignite mining and related potential environmental problems of lignite utilization. Chapter 10 is the "Selected Lignite Bibliography," which includes additional publications of possible interest.

Geopressured Geothermal Energy Potential. A giant energy resource may exist that has received little attention until recently and has certainly not been included in Federal estimates of total available energy. Known western geothermal regions have experienced a slow but steady history of technological development over the past few decades. New geothermal discoveries outside the well-known Geysers area have been made recently and new geothermal electrical generating plants are in the planning stages (Keplinger, 1976).

In the South-Central United States, recent estimates have been made that suggest that the subsurface geopressured brines alone may be capable of producing 100 quadrillion (10^{15}) Btu from the heat content of the produced brine. In addition, natural gas may be in saturated solution and if present could contribute an additional 500 quadrillion (10^{15}) or more Btu of recoverable energy (Brown, 1976).

Geopressured geothermal energy may indeed be a sleeping giant among alternate energy resources. Its development is directly related to petroleum engineering and technology, and with present or near-term technology, the resource may become economically recoverable. However, further evaluations must indicate favorable economics and technology. The apparent problems regarding environmental and institutional factors must also be favorably resolved.

In Part III of the text, Chapter 11 deals with the frontier or regional potential of geopressured geothermal energy and the geological factors and exploration techniques involved. Chapter 12 explores the techniques of local evaluation of prospective geopressured geothermal trend areas. Chapter 13 is a review of the potential utilization of the geopressured geothermal resource. Chapter 14 is an analysis of the environmental aspects of the development of the resource. Chapter 15 is the "Selected Geopressured Geothermal Bibliography," which also includes recent publications on the subject of additional interest.

Although many geological, engineering, environmental, and institutional problems are apparent, the development of the alternate energy resources of the South-Central United States as explored in this text could significantly add to the total available energy resource of the United States. But, before nuclear, fossil fuel or geopressured geothermal energy can be fully developed and utilized, the resources first must be located via many of the geological techniques discussed in this text. And, before the resources can be used on a broad scale, the environmental aspects must be evaluated to assure that the safety and well-being of society will not be negatively affected. This effort also involves many of the geological techniques of evaluation that are treated in the following chapters. Although the exploration and development of the three resources involve many unique approaches and techniques, all three are natural resources that first require geological assessment, hence the importance of a solid geological foundation in alternate energy development and the supporting need for *Geology of Alternate Energy Resources in the South-Central Unites States*.

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Houston, Texas

Michael D. Campbell
Editor

REFERENCES

Anonymous, 1975, Westinghouse: The waiting period: Forbes, December 1, pp. 24-26.

Anonymous, 1976a, Efforts at nuclear disposal made: Oilweek, September 13, pp. 32, 36, 40.

Anonymous, 1976b, Can Carter debottleneck nuclear power?: Chemical Week, November 17, pp. 17-18.

Anonymous, 1976c, Overplayed hand?: Forbes, September 15, pp. 53-54.

Anonymous, 1976d, The uranium dilemma: Why prices mushroomed: Business Week, November 1, pp. 92, 97.

Anonymous, 1976e, Why coal gasification is leaving the West: Business Week, September 13, pp. 76J-76O.

Anonymous, 1977, Recovery plant go-ahead for Uncle Sam: Mining Week, January 7, pp. 5-6.

Boyden, T. A., 1975, The marketing of uranium, *In* Colorado Mining Association Yearbook, pp. 110-113.

Brown, W. M., 1976, A huge raw reserve of natural gas comes within research: Fortune, October, pp. 219-222.

Campbell, M. D., 1976, Alternate energy and mineral development: General outlook and comparative economics: A paper presented at the 1976 Keplinger Energy Seminar, University Club, New York City, November 23, 30 pp.

Doctor, R., and others, 1976, The California nuclear safeguards initiative: Sierra Club Bulletin, vol. 61, no. 5, May, pp. 4-6, 44-46.

Energy Resources Council, 1976, Uranium reserves resources and production: NTIS PB-254-896, June, 14 pp.

Feiveson, H. A., and T. B. Taylor, 1976, Security implications of alternative fission futures: Bull. Atomic Scientists, vol. 32, no. 10, December, pp. 14-17.

Hendrickson, T. A., 1975, Synthetic Fuels Data Handbook, Cameron Engineers, Inc. Colorado, pp. 161-231.

Keplinger, C. H., 1976, OPEC oil price enhances U. S. geothermal development: World Oil, August.

Macgregor, W., and E. L. Vickers, 1974, Capital and the U. S. resources crunch: Eng. Mining Journ., Reprint R-209, 6 pp.

Newell, G. 1976, Hydrogen fusion shows promise of becoming ultimate energy source: Oilweek, September 13, pp. 22, 26, 28.

Parks, J. W., and D. C. Thomas, 1976, Plans for operating enrichment plants and the effects on uranium supply: Uranium Industry Seminar, U. S. ERDA, Grand Junction, October 19-20.

Pforzheimer, H., 1976, Commercial development of oil shale: forecast goes from cloudy to bleak: Eng. Mining Journ., vol. 177, no. 8, August, pp. 81-83.

Ross, R. C., 1975, Uranium recovery from phosphoric acid nears reality as a commercial uranium source: Eng. Mining Journ., December, pp. 80-85.

U. S. Department of Interior, 1975, Energy perspectives, February, 12 pp.

Winger, J. G., and C. A. Nielsen, 1976, Energy, the economy and jobs, *In* Energy Report from Chase, September, 8 pp.

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Chapter 1

Frontier Areas and Exploration Techniques

Frontier Uranium Exploration in the South-Central United States

ABSTRACT: Selected areas of the South-Central United States outside the known uranium trends of South Texas have a largely untested potential for the occurrence of significant uranium mineralization. These areas, underlain by Tertiary and older sediments, include parts of Texas, Oklahoma, Arkansas, Louisiana, Mississippi and Alabama. The commonly accepted criteria employed in uranium exploration are applicable to these "frontier" areas but special consideration must also be given to the atypical geologic aspects of such areas as they may apply to relatively unique types of uranium mineralization or to the development of special exploration criteria for common types of roll-front and fault-and dome-related uranium mineralization.

The procedures used in evaluating "frontier" areas should be based on comprehensive evaluations involving: 1) location and analysis of potential source rocks (e.g. intrusive igneous rocks, bentonitic sediments, unique complexes, etc.); 2) definition of regional variations in the potential host sediments (e.g. marginal marine to nonmarine environments of deposition); 3) review of all available radiometric data in Tertiary or older rocks; 4) local ground-water sampling (using a specific suite of major and minor elements selected on the basis of the regional ground-water geochemistry; 5) widely-spaced reconnaissance (or stratigraphic) drilling, coring and borehole geophysical logging to define favorable sedimentary facies and to establish the specific lithologic character of the sediments; and 6) detailed petrographic evaluation of all available samples to define the environment of deposition and diagenetic history of "favorable" sediments.

If procedures produce favorable results, suggesting that conditions for the formation of uranium mineralization are present in the area under consideration, an expanded exploration program is justified. Depths up to 3,000 feet should be anticipated if up-dip information is favorable. Selected areas are discussed that have: 1) favorable source and host rocks; 2) favorable age; 3) favorable regional and local structure; and 4) radiometric characteristics favorable for uranium mineralization of potentially economic grade and reserves in the areas.

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Chapter 2

Trend Areas and Exploration Techniques

South-Texas Uranium: Geologic Controls, Exploration Techniques, and Potential*

ABSTRACT: Host rocks for uranium in the South-Texas Coastal Plain are Tertiary sedimentary rocks that dip gently to the southeast toward the Gulf of Mexico and into the Gulf Coast geosyncline. The uranium host rocks are mainly porous sandstone units found in the upper Eocene Whitsett Formation, the Oligocene (?) Frio Clay, and the Miocene Catahoula Tuff and Oakville Sandstone. The sandstone units are of fluvial origin except for some in the Whitsett that were deposited in a beach environment.

The primary source of uranium in the South Texas deposits was probably the Catahoula Tuff. The uranium was dissolved under mildly alkaline, oxidizing conditions accompanying the semi-arid climate that was apparently predominant throughout the late Tertiary in the South Texas area. The dissolved uranium was transported in streams or underground conduits to an area of strong chemical reduction, where it was precipitated. Carbonized plant fragments in the host rock and H_2S emanating from petroleum deposits may have provided the chemical reductant.

Uranium deposits in South Texas have been found in three principal areas, each characterized by a different host rock. The principal host rocks are the Whitsett Formation in the Karnes County area, the Oakville Sandstone in the Live Oak County area, and the Catahoula Tuff in the Duval County area. Extensive open-pit mining in the Karnes area has allowed detailed studies. In this area the Catahoula Tuff lies unconformably on the Whitsett host rock. Uranium-bearing surface waters draining Catahoula Tuff terrane, or areas where pre-existing uranium deposits were located, were transported in streams or in subsurface paleochannel and beach sandstone units to the sites of deposition. Paleochannels are common in both the Whitsett and in the basal part of the Catahoula.

The ore bodies are generally in the form of rolls that are elongate perpendicular to the direction of ground-water movement and that are crescent-shaped in cross-section. The wings of the crescent point in the direction from which the uranium-bearing ground-water came, which is generally updip to the northwest in the general area under review. The ore minerals in most of the deposits are coffinite and uraninite, except in the ore bodies at or near the surface in the oxidized zone where autunite and tyuyamunite predominate.

Exploration techniques have generally consisted of surface mapping, drilling and logging, and airborne and surface radiometric studies. New exploration tools will become important as the search for new deposits extends deeper into the subsurface. Various airborne, surface, and in-hole

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*Publication authorized by the Director, U. S. Geological Survey.
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Resource Development/Utilization

Uranium In-Situ Leaching in the Tertiary Deposits of South Texas

ABSTRACT: The dévelopment of Texas uranium deposits of Eocene, Miocene and Pliocene age by *in-situ* leaching methods is in progress at six locations in Webb, Duval and George West Counties. Production trends are reviewed and show that a substantial increase in industrial activity has occurred over the past few years. Field techniques in preparing for development are discussed. The mineralogy, geochemistry, physical qualities of the host sandstones, and local ground-water conditions vary with each deposit but are generally compatible with the dissolution chemistry of alkaline-type leaching agents. A classification is discussed which relates geologic formations permeability, calcite, quartz, clays, pyrite, organic carbon and the commercial leaching processes. The environmental impact of subsurface solution mining in Bee County is explored from an industrial viewpoint.

INTRODUCTION

The modern solution-mining process for the recovery of uranium by borehole techniques is primarily a Texas development, with Colorado, Wyoming and Australia now following the Texas lead (ERDA, 1974). Each of the other uranium-producing states—Wyoming, Colorado, New Mexico, Washington and Utah have similar uraninite-coffinite sandstone deposits, but recognition of the favorable operating and capital costs of the process first occurred in Texas, and the feasibility of producing low-grade deposits was accepted. Thus, when process development had advanced to the point of commercial feasibility identified resources, sometimes with "probable ore" reserve status, had already been located by the explorationist and were available to producers.

The result is that an impressive list of producers has developed over a time span which is indeed short by mining industry standards. The present producers are indicated in Table 1. The locations of the operations are within the Texas Uranium Belt and range from Bruni, Webb County in the west to Beeville, Bee County in the east (Figure 1). Dickinson and Duval (this volume) discuss the geological aspects of many of the mines in the region. Briefly, the westernmost deposits are located in sand facies of the Catahoula Tuff; the eastern deposits lie in the basal Oakville Sandstone (Eargle and Weeks, 1973). The Palangana Salt Dome deposit of Duval County now being worked by Union Carbide is reported to be in the Goliad Formation.

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Environmental Considerations

Environmental Impacts of Uranium Mining in South Texas*

ABSTRACT: Recent investigations of uranium mining and milling activities in the Grants Mineral Belt of New Mexico revealed serious environmental problems associated with these activities. An investigation was undertaken in the South Texas Uranium Belt to determine whether or not similar or other environmental problems existed. The study describes: (1) the history of uranium mining and milling in South Texas, (2) the area economy and demography, (3) the occurrence of uranium ore and (4) the regulatory aspects of uranium mining and milling in South Texas. The commercial recovery and processing of uranium in this area is described in some detail. Exploration, open pit mining, *in-situ* solution mining and processing techniques for "yellowcake" (U_3O_8), the uranium product of the area, are discussed. The state and federal regulations pertinent to uranium mining and milling are summarized. Finally, the environmental effects of these activities are discussed and conclusions and recommendations are drawn.

INTRODUCTION

Texas is the most recent state to become a major producer of uranium. Early exploration in western Texas did not reveal significant deposits; however, late in 1954, uranium deposits were discovered, quite by accident, in an environment previously considered unfavorable. Along a 300-mile belt from East-Central to South Texas, as many as 25 prospects were discovered in the upper Eocene to Pliocene rocks.

Extensive exploration followed. Airborne radiometric surveys were conducted by oil, mining and exploration companies. The U. S. Geological Survey explored a 70,000-square-mile area and published both airborne and surface radiometric maps. It is estimated that the South Texas uranium district contains about 5 percent of the U. S. proven reserves of this metal.

Open-pit mining began in 1960 in a cluster of shallow (less than 50 feet deep) oxidized ore bodies in Karnes County. Milling operations soon followed. Deeper unoxidized ores were located in 1963 at a depth of about 100 feet and open-pit mining of these deposits began and is continuing today. Even deeper ore bodies between 200 and

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Selected Uranium Bibliography

URANIUM GENESIS

Ahrens, L. H., 1965, Some observations on the uranium and thorium distributions in accessory zircon from granitic rocks: Geochim. et Cosmochim Acta, vol. 29, pp. 771-776.

Andreyev, P. F., and others, 1962, Reactions of uranyl salts with components of plant tissue and some of their derivatives: Geochemistry, no. 4, pp. 359-364.

Baas Becking, L. G. M., and D. Moore, 1961, Biogenic sulfides: Econ. Geol., vol. 56, pp. 259-272.

Baranov, V. I., and others, 1956, Geochemistry of dispersed thorium and uranium in clays and carbonate rock of The Russian Platform: Geochemistry, no. 3, pp. 227-235.

Berglof, W., 1970, Absolute age relationships in selected Colorado Plateau uranium ores: Ph.D. Dissertation, Columbia Univ., 149 pp.

Bossi, J., 1974, Use of fluid inclusions in the genetic study of vein deposits: Proc. Int. Atomic Energy Agency Sym. (Athens, Greece) pp. 583-592.

Breger, I. A., 1974, The role of organic matter in the accumulation of uranium: the organic geochemistry of the coal-uranium association: Proc. Int. Atomic Energy Agency Symposium (Athens, Greece), pp. 99-135.

Bunker, C. M., and J. A. Mackallor, 1973, Geology of the oxidized uranium ore deposits of the Tordilla Hill-Deweesville Area, Karnes County, Texas: A study of a district before mining: U. S. Geol. Survey Prof. Paper 765, 37pp.

Currens, C. W., 1956, The geochemistry of the halogens: Physics and Chemistry of the Earth, vol, 1, pp. 181-233.

Derry, D. R., 1960, Evidence of the origin of the Blind River uranium deposits: Econ. Geol., vol. 55, pp. 906-927.

Dooley, J. R., Jr., and others, 1964, Radioactive disequilibrium studies of roll features, Shirley Basin, Wyoming: Econ. Geol., vol. 59, pp. 586-595.

Eargle, D. H., and A. D. Weeks, 1961, Possible relation between hydrogen sulfide-bearing hydrocarbons in fault-line oil fields and uranium deposits in the Southeast Texas Coastal Plain: U. S. Geol. Survey Prof. Paper 424—D, pp. D7-D9.

El Shazly, and others, 1974, Origin of uranium in Oligocene Qatrani sediments, Western Desert, Arab Republic of Egypt: Proc. Int. Atomic Energy Agency Symposium (Athens, Greece), pp. 467-478.

Frondel, C., 1958, Systematic mineralogy of uranium and thorium: U. S. Geol. Survey Bull. 1064, 62 pp.

Gabelman, J. W., 1970, Speculations on the uranium ore fluid: Uranium Exploration Geology, Proc. IAEA (Vienna), pp. 315-330.

Garrels, R. M., 1955, Weathering of uranium deposits: Mining Congress Journ., vol. 41, no. 5.

Garrels, R. M., and others, 1959, Detailed chemical and mineralogical relations in two vanadium-uranium ores: U. S. Geol. Survey Prof. Paper 320, pp. 165-184.

Gornitz, V. M., 1969, Mineralization, alteration and mechanism of emplacement, Orphan ore deposit, Grand Canyon, Arizona: Ph.D. Dissertation, Columbia Univ., 186 pp.

Gottfried, D., and E. S. Larsen, 1959, Distribution of uranium and thorium in igneous rocks: U. S. Atomic Energy Comm. Pub. TEI-752, pp. 70-90.

Granger, H. C., 1963, Radium migration and its effect on the apparent age of uranium deposits at Ambrosia Lake, New Mexico: U. S. Geol. Survey Prof. Paper 475B, pp. B60-B63.

Granger, H. C., and C. G. Warren, 1974, Zoning in the altered tongue associated with roll-type uranium deposits: Proc Int. Atomic Energy Agency Symposium, (Athens, Greece), pp. 185-200.

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Chapter 6

Frontier Areas and Exploration Techniques

Frontier Lignite Exploration in the South-Central United States

ABSTRACT: Lignite has become a viable alternate energy resource in the South-Central United States and has received much attention from both industry and the academic community. Studies of Holocene fluvial, deltaic, and lagoonal depositional environments can be used to construct models of Tertiary depositional systems that contain lignite-bearing component facies. These models adequately explain the occurrence and properties of near-surface and deep-basin Tertiary lignites in Texas, Arkansas, Louisiana, Alabama, and Mississippi. In addition, they offer great potential when used as interpretive tools in the initial stages of an exploration program leading to mine development. The stages of an effective program include the following: 1) exploration-target selection, 2) reconnaissance exploration, 3) detailed exploration, 4) development feasibility study, 5) phase one development program, 6) conceptual mine-design study, 7) phase two development program, and 8) final development and mine design.

INTRODUCTION

The reasons that coal can be viewed as the fossil fuel of the future have been covered amply in the literature (e.g., Risser, 1960; Hammond and others, 1973; Ezra, 1976; Smith, 1977, Scarrah and Calkins, in press; Campbell, this volume); however, the single most compelling reason for this view can be attributed to the fact that total coal resources greatly exceed all other fossil-fuel resources combined. Until a few years ago, coal, in the form of tremendous quantities of lignite, had been utilized only on a limited scale in the South-Central United States (Selvig, and others 1950; (see Figure 1), but this trend has changed. Lignite exploration, mining, and use has accelerated markedly in this region to meet growing energy

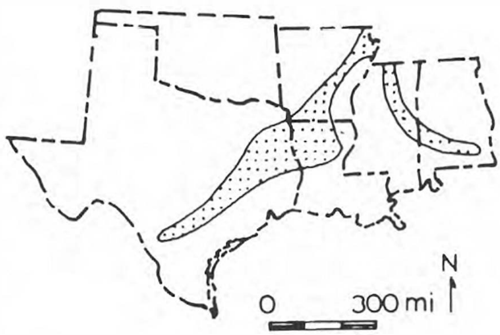

FIGURE 1. Lignite occurrence in the Tertiary of the South-Central United States (adapted from Averitt, 1969).

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Chapter 7

Trend Areas and Exploration Techniques

Occurrence and Characteristics of Midway and Wilcox Lignites in Mississippi and Alabama

ABSTRACT: Lignites occur in the Gulf Coastal Plain of Mississippi and Alabama in a number of formations ranging in age from Upper Cretaceous to Miocene. However, deposits of potential economic significance are found only in the Naheola Formation of the Midway Group (Paleocene) and in the Nanafalia, Tuscahoma, and Hatchetigbee Formations of the Wilcox Group (lower Eocene), and in undifferentiated Wilcox sediments.

At the outcrop, the Midway and Wilcox Groups attain a maximum thickness of about 1,200 feet (366 m) and are composed of terrigenous sediments deposited in fluvial, deltaic, and shallow marine environments. The sequence in Mississippi is predominantly fluvial and deltaic, while the equivalent units in Alabama accumulated in deltaic and shallow marine environments. The regressive nonmarine intervals are characterized by thick sequences of relatively nonfossiliferous cross-bedded sands; laminated to thin-bedded sands, silts and clays, and lignite. The shallow-marine transgressive units are generally thin and consist of fossiliferous, glauconitic, argillaceous sands and limestones.

Lignite in the Midway Group occurs as seams up to 14 ft (4.3m) in thickness at or near the top of the Oak Hill Member of the Naheola Formation. In Mississippi the Oak Hill Member is unconformably overlain by the nonmarine Fearn Springs Member of the Nanafalia Formation, while the glauconitic sands of the Coal Bluff Marl Member unconformably overlie the Oak Hill Member in Alabama. The Oak Hill lignite generally occurs as a single uninterrupted seam extending across western Alabama and east-central Mississippi.

In the Wilcox Group, lignite is present in the Gravel Creek Sand Member of the Nanafalia Formation in eastern Alabama, in the upper nanafalia of east-central Mississippi, in the upper Tuscahoma and the Hatchetigbee Formations in east-central Mississippi and western Alabama, and in undifferentiated non-marine sediments of north-central and northern Mississippi.

Lignite in the Gravel Creek Sand Member occurs as highly lenticular seams (up to 40 ft/12.2 m thick) which rarely exceed one mile in width. Deposition of these lignites apparently occurred in solutional or erosional channels developed in the upper Clayton limestone (Midway). The lignites are conformably overlain by the "*Ostrea thirsae* beds" of the Nanafalia Formation.

The lignites of the upper Nanafalia and the Tuscahoma and Hatchetigbee Formations occur as multiple seams within fluvial and deltaic sequences. These seams rarely exceed 10 ft (3.0 m) in thickness and are intermediate in areal extent between the Oak Hill seam and lignites of the Gravel Creek Sand Member.

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Chapter 8

Resource Development/Utilization

The Potential of In-Situ Lignite Gasification in Texas

ABSTRACT: The technical and economic feasibility of utilizing *in-situ* gasification to recover energy from deep basin Texas lignite has been under investigation during the past three years at UT - Austin. The low-Btu gas produced can be utilized for production of electric power or as a chemical feedstock. The economic and technical factors which make the *in-situ* process attractive have been indentified. Potential problem areas have also been evaluated. A discussion of previous operating experience in the U. S. and Russia will be given. Since Texas lignite is a shrinking coal, a three-step conversion process is envisioned: 1 drying; 2 backward burning; 3 forward burning. Steps 1 and 2 are permeability enhancement (seam preparation) processes, while the final step is the major gas production step. Laboratory work is presently under way to determine which geological, physical, and chemical conditions in Texas are condusive to economic application of *in-situ* gasification, and to develop a design and operating basis for eventual field testing.

INTRODUCTION

Underground coal gasification (UCG) has as its objective the recovery of the energetic and chemical content of coal without mining. A gaseous mixture composed of nitrogen, oxygen, steam, and carbon dioxide in variable proportions is introduced in a coal seam prepared for gasification; combustion and gasification reactions occur *in-situ*. The products, carbon monoxide, carbon dioxide, hydrogen, water vapor, methane, nitrogen and other hydrocarbons are obtained in a readily usable form for the production of electric power or the manufacture of chemicals.

In-situ coal gasification is a process which should be considered as a competitor with shaft mining but not with surface mining. The successful application of this method would provide a low-Btu gas (100-300 Btu/SCF) which is relatively clean (for sulfur compounds) and at the same time eliminate many of the health, safety, and environmental problems associated with conventional deep mining of coal. The *in-situ* method also has the potential to recover the energy from deep coal deposits which are not economic to mine by conventional schemes.

The idea of underground coal gasification is not new and dates back to one century ago. Historical reviews of the pre-1965 technology for UCG can

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Environmental Considerations

Environmental Aspects of Lignite Mining in the South-Central United States

ABSTRACT: Surface minable lignite occurs in Texas, Arkansas, Louisiana, Mississippi, and Alabama. This energy resource is becoming economically more attractive as energy costs continue to rise, but to be competitive with other fuels it is likely that production will be limited to large surface mines. Because surface mines commonly discharge water to nearby streams, they are subject to provisions of the Federal Water Pollution Control Act so that NPDES permits will be required. Regulations on new source standards for coal surface mines are imminent. These regulations will bring, for the first time, a full NEPA (National Environmental Policy Act) review to surface coal mining on private land, which includes most of the lignite deposits of the South-Central United States. State regulations will also have to be met and currently they are most comprehensive in Texas.

Unresolved environmental problems due to inadequate pre-mine inventories, analyses, or planning can contribute to unnecessary delays of one to several years, if US-EPA requires an environmental impact statement. If applicants prepare comprehensive pre-mine plans, which include analyses of potential environmental problems and measures to mitigate them, then US-EPA may use these data to issue a negative declaration and thereby speed up the process of NPDES permits. The environmental analyses should include environmental inventories, reclamation plans, post-mine land-use plans, and strategies to maintain water quality.

INTRODUCTION

As the nationwide and worldwide shortages of energy become more apparent, and as the cost of energy rises, lignite will increasingly become a competitive alternate fuel. Because the lignite of this area generally contains significant quantities of moisture and ash, it has an "as received" heating value of less than 9,000 BTU per pound (see Self and Williamson, this volume). Transportation costs of lignite, therefore, are generally prohibitively high, even over relatively short distances, and there also are ash disposal problems. Consequently, current conditions suggest that large-scale, surface lignite mines will supply mine-mouth electric generating stations. In the future other large energy-consuming industries, as well as industries that utilize lignite as a chemical raw

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Selected Lignite Bibliography

LIGNITE EXPLORATION

Adams, D. H., 1976, Objectives and organization of coal exploration projects, *In* Coal Exploration, Proc. First Int. Coal Exploration Sym. (London-May 18, 1976): Miller Freeman, Pub., San Francisco, pp. 89-103.

Adams, F. C., and others, 1927, Lignite in the Wilcox Formation of Texas east of the Trinity River: Houston, Tex.: Open File Rept., Texas Bur. Econ. Geology, 104 pp.

Anonymous, 1975, U. S. coal resources and reserves: Monthly Energy Rev., July, pp. 2-11.

Atlee, W. A., and others, 1968, Environments of deposition, Wilcox Group, Texas Gulf Coast: Houston Geol. Soc., Field Trip Guidebook, 43 pp.

Bernard, H. A., and others, 1970, Recent sediments of Southeast Texas—a field guide to the Brazos alluvial and deltaic plains and the Galveston Barrier Island complex: Texas Bur. Econ. Geology Guidebook II, 132 pp.

Bond, L. O., and others, 1971, Well-log applications in coal mining and rock mechanics: AIME Trans, vol. 250, December, pp. 355-362.

Clarke, A. M., 1966, Pay-off vs. risk assessments in planning & mining geology: Mining Engineer, vol. 73, October, pp. 29-46.

Clarke, A. M., 1976, Seismic surveying and mine planning: their relationship and application, *In* Coal Exploration, Proc. First Int. Coal Exploration Sym. (London - May 18-21, 1976): Miller Freeman Pub., San Francisco, pp. 158-191.

Daly, T. E., and R. F. Hagemann, 1976, Seismic methods for the delineation of coal deposits, *In* Coal Exploration, Proc. First Int. Coal Exploration Sym. (London - May 18-21, 1976): Miller Freeman Pub., San Francisco, pp. 192-226.

Deussen, A., 1924, Geology of the coastal plain of Texas west of Brazos River: U. S. Geol. Survey Prof. Paper 126, 145 pp.

Dumble, E. T., 1918, The geology of East Texas: Univ. Texas Bull. 1869, pp. 275-291.

Eargle, D. H., 1968, Nomenclature of formations of Claiborne Group, middle Eocene, coastal plain of Texas: U. S. Geol. Survey Bull. 1251-D, 25 pp.

Ellison, R. D., and A. G. Thurman, 1976, Geotechnology: an integral part of mine planning, *In* Coal Exploration, Proc. First Int. Coal Exploration Sym. (London - May 18-21, 1976): Miller Freeman, San Francisco, pp. 324-369.

Elsik, W. C., (In Press), Palynology of Gulf Coast lignites: the stratigraphic framework and depositional environments, *In* Kaiser, W. R., (ed.), Proc. Gulf Coast Lignite Conf: Geol., Utiliz. and Environ. Aspects: Texas, Bur, Econ. Geology.

Evans, T. J., 1974, Bituminous coal in Texas, Texas Bur. Econ. Geology, Handbook 4, 65 pp.

Evans, T. J., 1975, Native bituminous materials in Texas: Texas Bur. Econ. Geology, Min. Res. Circ. No. 57, 18 pp.

Fisher, W. L., 1964, Sedimentary patterns in Eocene cyclic deposits, northern Gulf Coast region: Kansas Geol. Survey Bull. 169, vol. 1, pp. 151-170.

Fisher, W. L., 1965, Rock and mineral resources of East Texas: Texas Bur. Econ. Geology, Rept. Inv. 54, 439 pp.

Fisher, W. L., 1968, Variations in lignites of fluvial, deltaic, and lagoonal systems, Wilcox Group (Eocene) Texas (abs.): Geol. Soc. America Ann. Mtg. Program, p. 97.

Fisher, W. L., 1969, Facies characterization of Gulf Coast basin delta systems, with some Holocene analogues: Gulf Coast Assoc. Geol. Socs. Trans., vol. 19, pp. 239-261.

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Frontier Areas and Exploration Techniques

Geopressured Geothermal Energy In The South-Central United States: Frontier Areas and Exploration Techniques*

ABSTRACT: Two frontier areas with great potential for geopressured geothermal energy development are located at the continental margin in the South-Central United States. Both are tectonic rift belts formed during early Mesozoic continental break-up; both were floored with thick deposits of Upper Jurassic salt; and both were sites of rapid sedimentation with contemporaneous salt diapirism. The Mississippi Salt Dome Basin occupies a rift which opened at the time the Gulf Basin was formed, but was superseded by a rift to the south, now occupied by the Gulf Coast geosyncline and the Gulf Coast Salt Dome Basin. Igneous activity in the Mississippi rift basin is widely known; the sedimentary fill indicating intense hydrothermal activity is perhaps less than half as thick as that in the Gulf Coast geosyncline and geopressured geothermal reservoirs occupy secondary porosity in consolidated rock, mainly Smackover carbonates and sandstones. Fluids are concentrated saline waters or diagenetic and metamorphic gases — CH_4, H_2S, and CO_2. Temperatures range from 356° - 482°F (180° - 250°C) at depths of 16,000 to 22,000 feet (4,880 to 6,710 m).

The Gulf Coast Salt Dome Basin occupies the Gulf Coast geosyncline and forms its gulfward margin. Igneous activity at depths is inferred, based upon salt mobilization features and the geotemperature regime of the noncarbonate clastic sediments that have filled the geosyncline since early Miocene time. Geopressured geothermal reservoirs are compartmentalized sand-bed aquifer systems having primary porosity, reduced by authigenic cements where temperatures range above 302°F (150°C). Fluids are saline waters ranging from less than 10,000 to 200,000 mg/1 or more; and diagenetic gases, mainly CH_4, but large volumes of CO_2 are known locally.

Exploration techniques are designed to determine and map five main parameters: 1) geotemperature, in terms of isothermal maps; 2) geopressure, in terms of iso-fluid pressure maps; 3) geothermal fluid reservoirs, generally sand-bed aquifers in the Gulf Coast Salt Dome Basin; 4) geologic structure, principally faults and folds; and 5) the salinity of formation waters, as isosalinity maps. Seismic and borehole logging methods are used in mapping fluid pressure; borehole logging methods provide data for isothermal mapping; seismic and borehole logging methods provide the data for structure mapping; borehole methods, mainly electric logging, provide the data for sand-bed reservoir mapping and for isosalinity mapping. Together, these maps provide the information necessary for selection and evaluation of prospects for geopressured geothermal energy development.

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Trend Areas and Exploration Techniques

Subsurface Techniques for Locating and Evaluating Geopressured Geothermal Reservoirs Along the Texas Gulf Coast*

ABSTRACT: A high percentage of the Texas Gulf Coast oil and gas is produced from the Frio Formation; most of the hydrocarbons are derived from fluvial sands on the updip portion of the Frio sedimentary wedge and are less than 100 feet thick. The downdip Frio sands are considerably thicker [100-700 feet (31-214 m)] and were deposited either as deltas or as strandplain deposits. These thick sands at depths greater than 10,000 feet commonly produce water fresher than sea water with temperatures between 250-300°F (122°-150°C) and are saturated with methane gas. The objective of the Bureau of Economic Geology project is to evaluate the potential of producing water from these large geopressured reservoirs in order to obtain thermal energy, methane gas, and potable water.

The first essential step in such an evaluation is to determine regional trends of the sand bodies and their depositional environments. Sand-percent maps of the lower part of the Frio outline thick dip-oriented sand bodies which were deposited as high-constructive deltas along the lower Texas Gulf Coast. To the north, along the middle and upper Texas Gulf Coast, sands along the main sand depocenter are strike-aligned and were deposited as strandplain sands and barrier bars. The sands of the upper part of the Frio, on the other hand, are predominantly strike-oriented throughout the Texas Gulf Coast.

Sand-percent maps along with isothermal maps identify gross geothermal fairways which contain sand bodies greater than 300 feet (92 m) thick with fluid temperatures higher than 250°F (122°C). More detailed studies of these fairways, then, incorporate both detailed analysis of sand distribution with closely spaced well-logs and porosity and permeability data obtained from core analysis and log interpretation.

INTRODUCTION

General. A potential geothermal reservoir along the Texas Gulf Coast should have a volume of at least three cubic miles (equivalent to cumulative thickness of 300 feet (92 m) and areal extent of 50 square miles (19.5 sq. km), uncorrected subsurface fluid temperature greater than 250°F (122°C), permeability greater than 20 millidarcies, and water saturated with methane.

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Chapter 13

Resource Development/Utilization

Development and Utilization of Geopressured Geothermal Resources in the South-Central United States*

ABSTRACT: The geopressured geothermal aquifers of the South-Central United States represent a potentially enormous store of mechanical, thermal and chemical energy. Nonetheless, it is not yet certain whether that energy can be utilized in ways that are technically sound, economically attractive and environmentally clean. This chapter reviews the principal issues and concerns related to the possible recovery and conversion of energy from the geopressured resource.

Geopressured brines occur in well-defined sandstone formations, or reservoirs, which vary widely in size, temperature and productive capacity. Plants capable of generating electricity from geopressured "fuel" would require certain minimum reservoir properties. To what extent Gulf Coast geopressured aquifers meet these criteria has not yet been determined. Less stringent reservoir requirements would govern the direct application of geopressured heat to industrial and agricultural processes.

The technical and economic feasibility of systems proposed for the extraction, conversion, and utilization of geopressured energy are examined in relation to resource properties. Concepts for the conversion of the mechanical and thermal energy components to electricity are discussed, and several approaches to nonelectric energy utilization are noted.

A brief review highlights the importance of legal and institutional issues that may impede the development of geopressured resources. It is concluded that a better understanding of geopressured resource characteristics is prerequisite to the resolution of most outstanding concerns, both technical and nontechnical.

INTRODUCTION

The utilization of geothermal resources is defined as the extraction of their energy content and its application to activities and processes that society considers useful. The principal constraints upon the extraction and application of energy from geopressured geothermal resources are related to technical feasibility, economic feasibility, effects upon the environment, and institutional factors. Present perceptions of the nature of geopressured

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Chapter 14

Environmental Considerations

Geothermal Resources of the Texas Gulf Coast—Environmental Concerns Arising From the Production And Disposal Of Geothermal Waters*

ABSTRACT: Disposal and temporary surface storage of spent geothermal fluids and surface subsidence and faulting are the major environmental problems that could arise from geopressured geothermal water production. Geopressured geothermal fluids are moderately to highly saline (8,000 to 72,000 parts per million total dissolved solids) and may contain significant amounts of boron (19 to 42 parts per million). Disposal of hot saline geothermal water in subsurface saline aquifers will present the least hazard to the environment. It is not known, however, whether the disposal of as much as 310,000 barrels (54,000m^3) of spent fluids per day into saline aquifers at the production site is technically or economically feasible. If saline aquifers adequate for fluid disposal cannot be found, geothermal fluids may have to be disposed of by open watercourses, canals, pipelines to coastal bays on the Gulf of Mexico. Overland flow or temporary storage of geothermal fluids may cause negative environmental impacts.

As the result of production of large volumes of geothermal fluid, reservoir pressure declines may cause compaction of sediments within and adjacent to the reservoir. The amount of compaction depends on pressure decline, reservoir thickness, and reservoir compressibility. At present, these parameters can only be estimated. Reservoir compaction may be translated in part to surface subsidence. When differential compaction occurs across a subsurface fault, fault activation may occur and be manifested as differential subsidence across the surface trace of the fault or as an actual rupture of the land surface.

The magnitude of environmental impact of subsidence and fault activation varies with current land use; the greatest impact would occur in urban areas, whereas relatively minor impacts would occur in rural, undeveloped agricultural areas.

Geothermal resource production facilities on the Gulf Coast of Texas could be subject to a series of natural hazards: (1) hurricane- or storm-induced flooding, (2) winds from tropical storms, (3) coastal erosion, or (4) expansive soils. None of these hazards is generated by geothermal resource production, but each has potential for damaging geothermal production and disposal facilities that could, in turn, result in leakage of hot saline geothermal fluids.

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Selected Geopressured Geothermal Energy Bibliography

GEOPRESSURED GEOTHERMAL ENERGY EXPLORATION

Albright, J. N., 1975, Temperature measurements in the Precambrian Section of Geothermal Test Hole No. 2: Los Alamos Sci. Lab. Rept. No. LA-6022-MS, July, 11 pp.

Anonymous, 1973, The potential for energy production from geothermal resources: U. S. Senate Comm. Interior and Insular Affairs Rept., December, 40 pp.

Anonymous, 1974, Project Independence: Task force report, geothermal energy: U. S. Fed. Energy Admin., November, 124 pp.

Anonymous, 1975, Geothermal activity picks up on federal acreage: Petrol. Eng., vol. 47, no. 7, July, p. 86.

Anonymous, 1975, A study of geothermal prospects in the western United States: Final Rept. No. 28455-6001-RU-00, (NTIS) N76-22665, Jet Prop. Lab., Calif. Inst. Tech., NASA, Aug. 20, 133 pp.

Anonymous, 1976, Report to the Congress: Problems in identifying, developing, and using geothermal resources: U. S. General Accounting Office, Rept. No. NP-20694, March, 78 pp.

Anonymous, 1976, Geopressured well will be studied in Louisiana, Ocean Ind., vol. 11, no. 6, June, pp. 125-126.

Anonymous, 1976, Geothermal energy promising but risky: Chem. Eng. News, vol. 54, no. 42, October 11, pp. 27-28.

Armstead, H. C. (ed.), 1973, Geothermal energy: UNESCO Press, vol. 12, Earth Sciences Series, 186 pp.

Aud, B., 1975, Reflection seismic techniques locate geopressured-geothermal anomalies, *In* Dorfman, M. H., and R. W. Deller (eds.), Proc. First Geopressured Geothermal Energy Conf.: Univ. Texas, Austin, Center for Energy Studies, pp. 133-144.

Averiev, V. V., 1964, The technique of testing geothermal wells: Proc. U. N. New Sources of Energy Conf. (Rome, 8/21-31/61), vol. 2, pp. 60-72.

Banwell, C. J., 1964, Geothermal drillholes: Physical investigations: Proc. U. N. New Sources of Energy Conf. (Rome, 8/21-31/61), vol. 2, pp. 60-72.

Banwell, C. J., 1970, Geophysical techniques in geothermal exploration: Proc. U. N. Sym. Develop. and Utiliz. of geothermal resources *In* Geothermics, Special Issue 2, vol. 1, Pisa, Italy, pp. 32-57.

Colp, J. L., and others, 1976, Magma Energy Research Project. Summary, July 1, 1974-June 30, 1975: NTIS SAND-75-0451, March, 38 pp.

Connolly, E. T., 1972, Geothermal survey of North America progress report and associated data-gathering problems: Trans. 45th Can. Well Logging Soc. Formation Evaluation Sym. (Calgary, May 9-10, 1972), Paper F, 37 pp.

Dorfman, M. H., 1976, Geothermal energy in the United States—An unexploited resource: Interstate Oil Compact Comm. Bull., vol. 18, no. 1, June, pp. 1-2.

Dorfman, M. H., and R. O. Kehle, 1974, Potential geothermal resources of Texas: Texas Bur. Econ. Geology, Circ. 74-4, 33 pp.

Durr, F., 1964, Operations research and possible applications to geothermal exploration programming: Proc. U. N. New Sources of Energy Conf. (Rome, 8/21-31/61), vol. 2, pp. 204-207.

Durvcan, E., and K. Olcenoglu, 1970, Geothermal drilling and preliminary test operations at Kizildere, Turkey: Proc. U. N. Sym. Develop. and Utiliz. of Geothermal Resources, *In* Geothermics, Special Issue 2, vol. 2, part 2, Pisa, Italy, pp. 1463-1466.

Gringarten, A. C.., and P. A. Witherspoon, 1973, Extraction of heat from multiple-fractured dry hot rock: Geothermics, vol. 2, nos. 3-4, September-December, pp. 119-122.

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